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Compartment Pressures in Children With Normal and Fractured Forearms: A Preliminary Report

Tharakan, Sasha J ; Subotic, Ulrike ; Kalisch, Markus ; Staubli, Georg ; Weber, Daniel M

Abstract: INTRODUCTION Acute compartment syndrome (ACS) can lead to irreversible damage if fasciotomy is not performed in a timely manner. Needle manometry is a tool to confirm suspected ACS. The threshold for compartment pressures that can be tolerated has been debated. The aim of this study is to assess the normal compartment pressures in noninjured forearms of children. Further, we sought to quantify the maximum tolerable compartment pressures in fractured forearms of children, thus establishing a baseline and providing guidance in evidence-based decision making to evaluate children with suspected ACS. METHODS This prospective study included children up to the age of 16 years with forearm fractures that needed reduction with or without osteosynthesis. Between June 2009 and March 2013, 41 children were included. Mean age was 9.25 years (range, 4 to 15.4 y). We used needle manometry to measure the pressures in the superficial and deep volar as well as in the dorsal compartments (DCs) on both the forearms. The mean pressures between compartments in healthy versus injured arms were analyzed using a 1-sided, paired t test. RESULTS On the injured side, the mean compartment pressure was 19.12 mm Hg (range, 3 to 49 mm Hg) in the deep volar compartment, 15.56 mm Hg (range, 5 to 37 mmHg) in the DC, and 14.8 mm Hg (range, 2 to 35 mm Hg) in the superficial volar compartment. On the noninjured side, the mean compartment pressure was 12.9 mm Hg (range, 6 to 31 mm Hg) in the DC, 10.22 mm Hg (range, 3 to 22 mm Hg) in the deep volar compartment, and 9.66 mm Hg (range, 3 to 21 mm Hg) in the superficial volar compartment. We measured an absolute compartment pressure of >30 mm Hg in 15 patients on the fractured side. Three of them had an absolute compartment pressure of >45 mm Hg. Only 1 had ACS. This patient underwent fasciotomy and was excluded for further analysis. On follow-up (mean, 24.84 mo), no patient was found to have any sequelae of ACS. DISCUSSION This is the first study to report normal compartment pressure measurements in noninjured forearms and in fractured forearms without clinical suspicion of ACS in children.The mean compartment pressure measured in the deep volar compartment (DVC) in healthy children was 10.22 mm Hg (range, 3 to 22 mm Hg) and therefore slightly higher than in adults. Some children with fractures tolerated absolute compartment pressures >30 mm Hg without clinical signs of ACS. Fasciotomy in children under close observation could eventually be delayed despite surpassing the accepted pressure limits for adults. LEVEL OF EVIDENCE Prognostic level I. See instructions to authors for a complete description of levels of evidence.

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Compartment Pressures in Children With Normal and Fractured Forearms: A Preliminary Report

Sasha J. Tharakan, MD, Ulrike Subotic, MD,* Markus Kalisch, PhD,† Georg Staubli, MD,‡ and Daniel M. Weber, MD**

Introduction: Acute compartment syndrome (ACS) can lead to irreversible damage if fasciotomy is not performed in a timely manner. Needle manometry is a tool to confirm suspected ACS. The threshold for compartment pressures that can be tolerated has been debated. The aim of this study is to assess the normal compartment pressures in noninjured forearms of children. Further, we sought to quantify the maximum tolerable compartment pressures in fractured forearms of children, thus establishing a baseline and providing guidance in evidence-based decision making to evaluate children with suspected ACS.

Methods: This prospective study included children up to the age of 16 years with forearm fractures that needed reduction with or without osteosynthesis. Between June 2009 and March 2013, 41 children were included. Mean age was 9.25 years (range, 4 to 15.4 y). We used needle manometry to measure the pressures in the superficial and deep volar as well as in the dorsal compartments (DCs) on both the forearms. The mean pressures between compartments in healthy versus injured arms were analyzed using a 1-sided, paired *t* test.

Results: On the injured side, the mean compartment pressure was 19.12 mm Hg (range, 3 to 49 mm Hg) in the deep volar compartment, 15.56 mm Hg (range, 5 to 37 mmHg) in the DC, and 14.8 mm Hg (range, 2 to 35 mm Hg) in the superficial volar compartment. On the noninjured side, the mean compartment pressure was 12.9 mm Hg (range, 6 to 31 mm Hg) in the DC, 10.22 mm Hg (range, 3 to 22 mm Hg) in the deep volar compartment, and 9.66 mm Hg (range, 3 to 21 mm Hg) in the superficial volar compartment. We measured an absolute compartment pressure of > 30 mm Hg in 15 patients on the fractured side. Three of them had an absolute compartment pressure of > 45 mm Hg. Only 1 had ACS. This patient underwent fasciotomy and was excluded for further analysis. On follow-up (mean, 24.84 mo), no patient was found to have any sequelae of ACS.

Discussion: This is the first study to report normal compartment pressure measurements in noninjured forearms and in fractured forearms without clinical suspicion of ACS in children. The mean compartment pressure measured in the deep volar compartment (DVC) in healthy children was 10.22 mm Hg (range, 3 to 22 mm Hg) and therefore slightly higher than in adults. Some children with fractures tolerated absolute compartment pressures > 30 mm Hg without clinical signs of ACS. Fasciotomy in children under close observation could eventually be delayed despite surpassing the accepted pressure limits for adults.

Level of Evidence: Prognostic level I. See instructions to authors for a complete description of levels of evidence.

Key Words: compartment pressure, pediatric, compartment syndrome, upper extremity

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Compartment syndrome is defined as increased pressure within a confined closed fascial space, causing subsequently reduced blood flow and tissue perfusion that often leads to ischemic pain and possible soft-tissue damage.[1] The damage from acute compartment syndrome (ACS) is often irreversible if fasciotomy is not performed in a timely manner.[2,3] Therefore, the diagnosis of a compartment syndrome is crucial. ACS has been well studied since the original publication by Richard von Volkmann in 1881. In this study, he described ischemic contractures of affected extremities as the late complications of ACS.[4] The classic clinical signs of ACS according to textbooks are well known and include: pain, paresthesia, paralysis, pulslessness, and pallor. However, pulslessness and pallor occur only if the arterial blood flow is significantly compromised. Most patients with ACS though, present with good peripheral pulses. As described by Bae and colleagues, these clinical signs are often relatively unreliable. They showed that 90% of their pediatric population with ACS due to fractures presented with pain, however, < 40% had pain and 2 additional classic clinical symptoms.[5] This illustrates that especially in young children, who may not have the cognitive or verbal ability to provide meaningful clinical information, diagnosis based solely on clinical signs is particularly challenging. Thus, quantitative methods to diagnose an impending ACS should be available. Irrespective of the age group, many authors recommend invasive intramuscular pressure measurements as an objective tool to confirm suspected ACS.

From the *Pediatric Hand Surgery, University Children's Hospital Zurich; †Seminar for Statistics, ETH Zurich; and ‡Department of Emergency Medicine, University Children's Hospital Zurich, Zurich, Switzerland.

The authors declare no conflicts of interest.

Reprints: Sasha J. Tharakan, MD, University Children's Hospital Zurich, Steinwiesstr. 75, 8032 Zurich, Switzerland. E-mail: sasha.tharakan@kispi.uzh.ch.

The indication for surgical decompression in suspected ACS can be based on the absolute maximum compartment pressure or on pressure gradients. Even in adults, the threshold for absolute maximum compartment pressure is debated, as pressures between 30 and 45 mm Hg have been considered abnormally elevated.[6,7] Many authors prefer to rely on the difference between the diastolic blood pressure and the compartment pressure, assuming that this more accurately reflects the perfusion of a compartment at risk. Dahn et al[8] showed that blood flow in microcirculation ceases when the tissue pressure in a compartment equals the diastolic blood pressure. A compartment pressure of 20 mm Hg below diastolic has been documented to significantly decrease tissue perfusion, resulting in ischemia and ischemic changes. Therefore, compartment pressures within 10 to 30 mm Hg of the diastolic blood pressure have been recommended as a threshold for surgical fasciotomy.[9–11]

Although these recommendations are based on data from adult patients, they are widely used for decision making in children as well. ACS of the lower extremity in children is well studied. There is 1 recent study that showed that the baseline compartment pressures in the legs of children are higher than in those of adults (average, 13.3 to 16.6 mm Hg for children, compared with 5.2 to 9.7 mm Hg for adults) and that the pediatric group may tolerate higher pressures than adults.[12,13] However, there are no data available for the upper extremity in the pediatric population.

The aim of this study is to assess the normal compartment pressures in noninjured forearms of children. To this end, we sought to quantify the maximum tolerable compartment pressures in fractured forearms of children, thus establishing a baseline and providing guidance in evidence-based decision making to evaluate children with suspected ACS.

METHODS

This prospective study included healthy children up to the age of 16 years with forearm fractures that needed reduction with or without osteosynthesis. Patients with bilateral fractures of the upper extremities and patients operated later than 24 hours postinjury were excluded.

Between June 2009 and March 2013, 41 children were included. There were 33 boys and 8 girls with a mean age of 9.25 years (range, 4 to 15.4 y). After obtaining a signed consent from the parents, all patients were brought to the operating room and had compartment pressure measurement under general anesthesia, fully relaxed and in supine position. Pressures were measured using a standardized method of simple needle manometry. Several techniques for compartment pressure measurement have previously been described, and assuming correct use, show equal effectiveness. These include: slit catheter, wick catheter, micro tip pressure probe, and needle manometer insertion.[14–16] Needle manometry is readily available, inexpensive, and accurate. We therefore chose needle manometry with the Stryker Pressure Monitor (Kalamazoo, MI) for our intraoperative measurements. All measurements were performed by experienced attendings. Special care was taken to place the forearm in a standardized and relaxed position to avoid false-positive elevated compartment pressures. We measured the pressures in the superficial and deep volar as well as in the dorsal compartments (DCs) on both forearms before surgery. The insertion site for the 18-G side-ported needle was between the proximal and middle third of the forearm on the volar and dorsal side, respectively (Fig. 1). After zero balancing, the needle was inserted in a 45-degree angle into the corresponding compartment and we injected 0.3 mL of normal saline. Once the equilibrium state was reached, the pressure was read off the monitor. The systolic and diastolic blood pressures were measured using a cuff.

The mean pressures between compartments in healthy versus injured arms were analyzed using a 1-sided, paired *t* test. For the relationship between age and pressure, a correlation test was used (based on Pearson correlation). For the relationship between pressures of different compartments within the same arm, simple linear regression with prediction intervals was used.

Four patients were excluded from the study because of missing compartment pressure values that were not obtained at the time of surgery. One patient with a clinical suspicion of an ACS and a compartment pressure of 50 mm Hg in the DVC had an immediate fasciotomy and was excluded for further evaluation.

All patients were admitted and hospitalized until pain was well controlled with oral analgesics.

Patients were followed in our outpatient clinic and we performed a structured telephone interview. All patients were seen 3 months postoperatively in the clinic. Wound and fracture healing, as well as motor and sensory function were assessed. During the telephone interview, patients were asked specific questions regarding pain, motor and sensory function, scarring, and potential problems with the insertion sites that were used for the compartment pressure measurements. Mean follow-up for our patient group was 24.84 months (range, 3 to 50 mo). Two patients were lost in telephone follow-up, but were seen in clinic 3 months postoperatively.

The Medical Ethics Committee approved this study.

RESULTS

Twenty patients sustained a both bone forearm fracture of which 1 was a type I open fracture. We treated 18 of them with a closed reduction and internal fixation (Titanium Elastic Nails), 2 were treated with closed reduction and casting. The fascia was not opened in these cases. Nineteen patients had a distal radius fracture and 2 patients had a Monteggia fracture.[17,18] Six of the distal radius fractures were treated with closed reduction and casting, 12 required closed reduction and percutaneous pinning with Kirschner wires, and 1 needed an open reduction and percutaneous pinning. In the case that required open reduction, the fascia was not suture closed. One Monteggia fracture was treated with closed reduc-

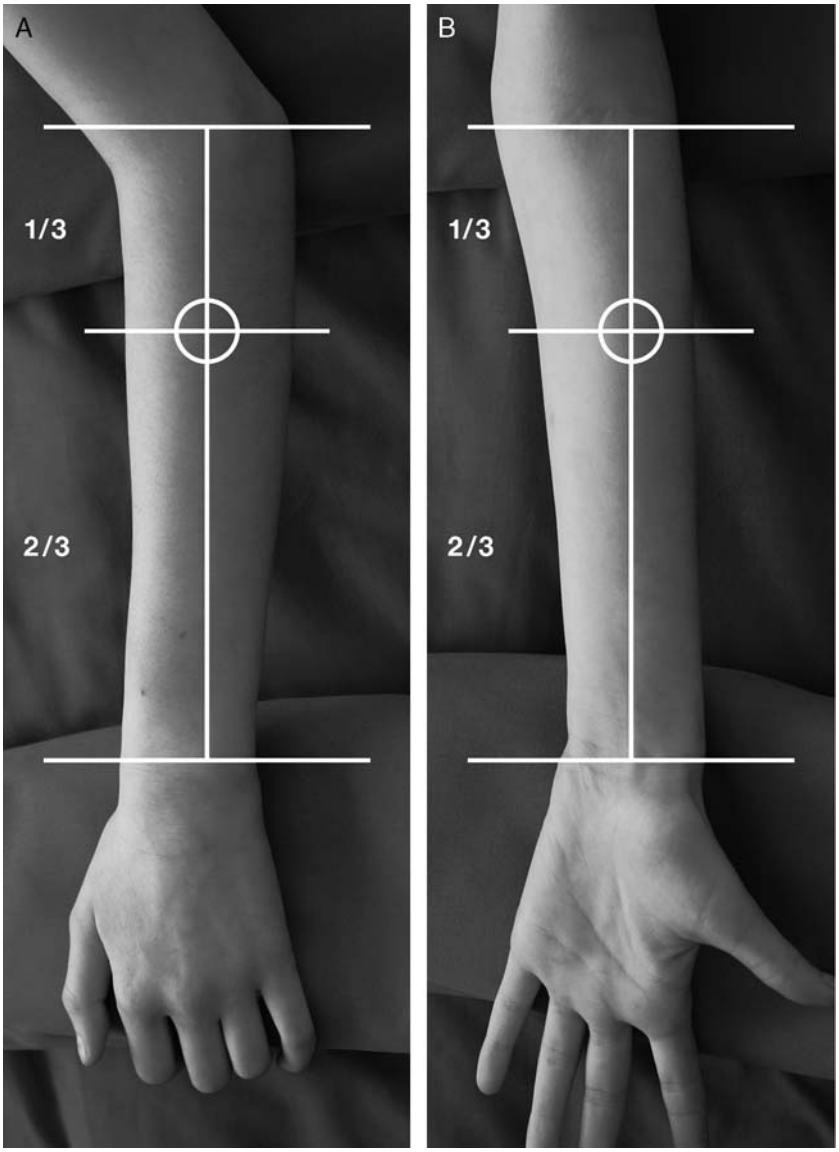

FIGURE 1. Compartment pressure measurement sites between the proximal and middle third of the dorsal (A) and volar (B) forearm.

tion and casting, the other one with closed reduction and internal fixation. No patient had significant soft-tissue injury, that is, from a run-over trauma.

TABLE 1. Mean Forearm Compartment Pressures (mm Hg) in Healthy and Fractured Forearms

	Age (y)	H SVC	F SVC	H DVC	F DVC	H DC	F DC
Mean	9.25	9.66	14.80	10.22	19.12	12.90	15.56
SD	3.03	4.20	7.38	4.86	11.36	5.90	8.00
Minimum	4.01	3.00	2.00	3.00	3.00	6.00	5.00
Maximum	15.35	21.00	35.00	22.00	49.00	31.00	37.00

DC indicates dorsal compartment; DVC, deep volar compartment; F, fractured; H, healthy; SVC, superficial volar compartment.

The mean compartment pressures for the 41 patients were higher for all 3 compartments on the fractured extremity than on the noninjured contralateral side. On the injured side, the highest mean pressures were measured in the deep volar compartment (DVC), followed by the dorsal compartment (DC), and finally the superficial volar compartment (SVC). The mean compartment pressure was 19.12 mm Hg (range, 3 to 49 mm Hg) in the DVC, 15.56 mm Hg (range, 5 to 37 mm Hg) in the DC, and 14.8 mm Hg (range, 2 to 35 mm Hg) in the SVC. On the uninjured side, we measured a mean compartment pressure of 12.9 mm Hg (range, 6 to 31 mm Hg) for the DC, 10.22 mm Hg (range, 3 to 22 mm Hg) for the DVC, and 9.66 mm Hg (range, 3 to 21 mm Hg) for the SVC (Table 1). The pressures among the various compartments on the fractured side correlated significantly but

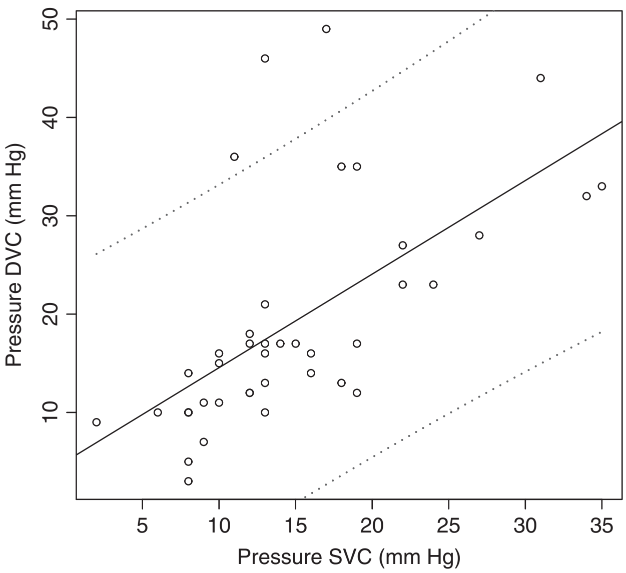

FIGURE 2. Regression line (solid line) between compartments on the fractured side together with 95%-prediction interval (dashed lines). Each open circle represents the correlated compartment pressures of one patient. DVC indicates deep volar compartment; SVC, superficial volar compartment.

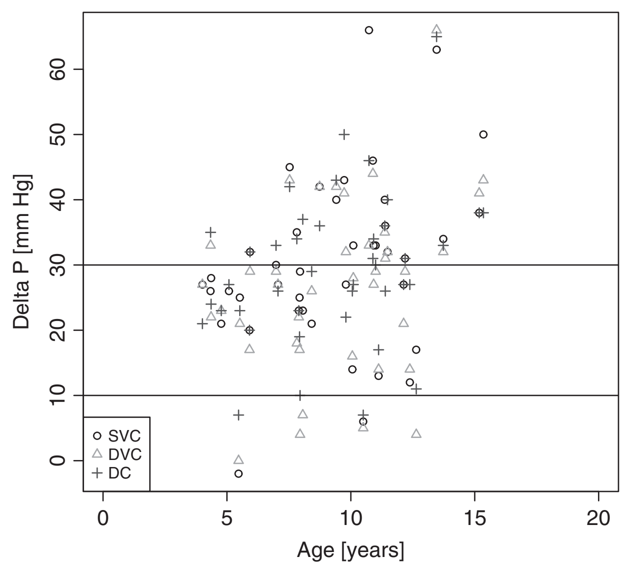

FIGURE 4. Perfusion gradient ΔP = diastolic blood pressure − compartment pressure on fractured side. Twenty-nine patients had a ΔP of <30 mm Hg in at least one of the compartments on the fractured side, 6 had a ΔP of <10 mm Hg in at least one of the compartments on the fractured side. DC indicates dorsal compartment; DVC, deep volar compartment; SVC, superficial volar compartment

with a wide prediction interval of 95% (Fig. 2). We measured an absolute compartment pressure of >30 mm Hg in 15 patients on the fractured side, of which 9 were in the DVC. Three of them had an absolute compartment pressure of >45 mm Hg (Fig. 3). Only one of these 3 patients had a preoperative clinical suspicion of ACS, which was confirmed with needle manometry, showing an intraoperative pressure of 50 mm Hg in the DVC. This patient underwent immediate fasciotomy and was excluded for further analysis to determine the threshold for maximum tolerable pressures. Figure 4 shows the calculated difference between the diastolic blood pressure and the compartment pressure (perfusion gradient, ΔP). Twenty-nine patients had a ΔP < 30 mm Hg in at least one of the compartments on the fractured side. Likewise, 6 patients had a ΔP < 10 mm Hg in at least one of the compartments on the fractured side, one of which was the patient who underwent fasciotomy.

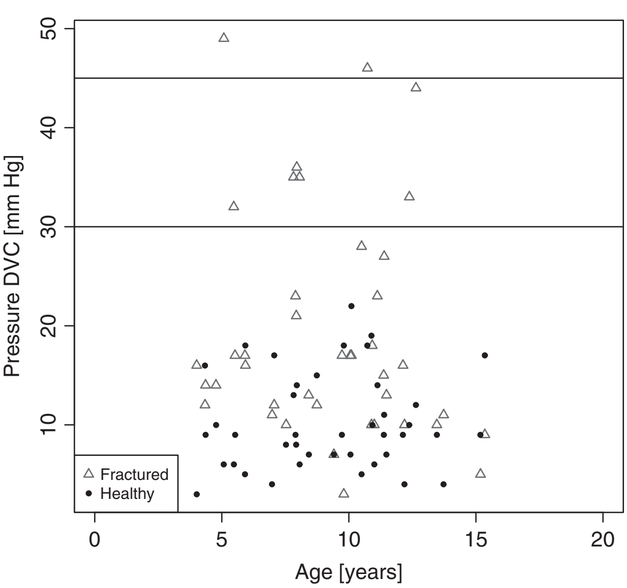

FIGURE 3. Absolute compartment pressure (mm Hg) in the deep volar compartment (DVC) on the fractured (triangle) and healthy (circle) side. Compartment pressures exceeded 30 mm Hg in 14 patients, of which 8 were in the DVC. Compartment pressures exceeded 45 mm Hg in 2 patients, both were in the DVC.

On the healthy side, 21 patients had a ΔP < 30 mm Hg in at least one of the compartments. One patient had a ΔP < 10 mm Hg in the DC on the healthy side.

We noted that 11 patients had a higher absolute pressure in the SVC on the noninjured side than on the corresponding compartment of the fractured side. The same was true for 9 patients in the DVC and in 13 patients in the DC. As expected, however, the mean pressure on the fractured side was significantly higher than on the healthy side (1-sided, paired *t* test; *P*-value for SVC: 0.0003, *P*-value for DVC: <0.0001, *P*-value for DC: 0.029).

There was no significant correlation between age and pressure in any compartment on the noninjured arm.

The 14 patients with compartment pressures of >30 mm Hg were postoperatively followed clinically for any symptoms of compartment syndrome. None of them required a fasciotomy or remeasuring with needle manometry.

On follow-up, no major complications were noted. Two patients noticed mild pain in cold weather in the area of their scars 19 months after closed reduction and internal fixation of a forearm shaft fracture and 6 months after closed reduction and percutaneous pinning of a distal radius fracture, respectively. One patient noted mild pain 17 months after closed reduction and internal fixation of a forearm shaft fracture. No patient was found to have any sequelae of ACS. The patients reported no problems related to the compartment pressure measurement sites.

DISCUSSION

To our knowledge, this is the first study to report normal compartment pressure measurements in noninjured and in fractured forearms without clinical suspicion of ACS in children.

Normal forearm compartment pressures in our pediatric population were similar to those reported in adults. The mean compartment pressure measured in the DVC in healthy children was 10.22 mm Hg (range, 3 to 22 mm Hg) and therefore slightly higher than in adults, 8.97 mm Hg (range, 0 to 17 mm Hg).[19] However, the small difference does not appear to be clinically relevant. This stands in contrast to the observations of Staudt et al[13] who reported higher baseline compartment pressures for the lower extremity in children than in adults.

Looking at the measured compartment pressures on the injured arm, we found a significant correlation between the various compartments but with a wide prediction interval. For example, if we were to measure a SVC pressure of 20 mm Hg in a particular patient, a 95% prediction interval for the DVC would be between 5 and 43. Furthermore, in our population some patients with normal pressures in 2 compartments had markedly increased pressures in the remaining compartment of the same injured arm. Hence, it is mandatory to measure the pressure in all compartments.

It is widely accepted that the indication for fasciotomy in adults is given for absolute compartment pressures of >30 to 45 mm Hg[6,7] or a perfusion gradient ΔP of <10 to 30 mm Hg.[9–11] Some authors consider the diastolic blood pressure to be a key factor. They argue that a patient with a higher diastolic blood pressure would more likely tolerate an absolute compartment pressure of 30 mm Hg than a hypotensive patient.[9,20,21] Children have a physiologically lower diastolic blood pressure than adults, resulting in a lower perfusion gradient with a given compartment pressure. One may therefore speculate that fasciotomy should be performed at lower compartment pressures in children than in adults. This, however, contradicts our observation of high compartment pressure tolerance that was seen in our population. We sought to quantify the maximum tolerable compartment pressures in fractured forearms in children. Because of our small sample size, it is difficult to pinpoint the exact zone between tolerable elevated compartment pressure and compartment syndrome. As our data demonstrate, some children with fractures tolerated absolute compartment pressures of >30 mm Hg or a ΔP of <10 to 30 mm Hg without clinical signs of ACS. Only 1 had clinical signs of ACS and underwent prompt surgical decompression. No fasciotomies were performed in the remaining 14 patients with compartment pressures of >30 mm Hg and none of them had any detectable late sequelae due to ACS at follow-up.

The limitations of our study include the small sample size and potentially the site of measurement for our compartment pressures. We chose the proximal third of the forearm as this correlated with the biggest muscle mass and circumference. We wanted to assure an easily identifiable, reproducible, and also safe spot for measurements. Heckman and colleagues found in their study that compartment pressure measurements peaked usually at the level of the fracture. The measured pressure decreased steadily when sampled at increasing distances proximal and distal to the site of the highest recorded pressure. Therefore, compartment pressures could be underestimated if measured too far from the fracture site.[10,22] This might have been the case in our patients with distal forearm fractures, but for practical reasons it would not be feasible to do multiple measurements along the arm.

One of the most cited studies to look at the accuracy in the measurement of compartment pressures is by Boody and Wongworawat.[14] They found that side-port needles and slit catheters are more accurate than straight needles for the measurement of compartment pressures. The Stryker manometer showed a confidence interval of $\pm$ 6.23 mm Hg if used with the side-ported needle as we did in our study. However, Hammerberg et al[15] showed in their study that when comparing slit catheters, side-ported needles and straight needles used with any available electronic digital transducer are equally useful and accurate. We measured the compartment pressures before the fracture was reduced. The compartment pressure might be lower after bringing the forearm to full length in a simple and easy to reduce fracture. Prolonged time to reduce the fracture, causing increased soft-tissue swelling, could attribute to increased compartment pressures after reduction of a severely displaced fracture. We intended to measure the compartment pressures before any manipulation to the forearm. If clinical suspicion arises, the measurements could be repeated at the end of the case. This was not necessary in our series of patients.

Thus, fasciotomy in children under close observation could eventually be delayed despite surpassing the accepted pressure limits for adults. In light of the scarce data available, it seems prudent to remember and respect the accepted threshold values in adults. However, the indication for fasciotomy is never based on compartment pressures alone. It cannot be emphasized enough that the clinical presentation surpasses any measured value. If in doubt, a fasciotomy should be performed.

Future techniques that allow continuous monitoring of metabolism or oxygenation within selected compartments may provide better quantitative parameters to diagnose ACS.[23]

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